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Techniques and criteria for sustainable urban stormwater management. The case study of Valdebebas (Madrid, Spain)

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ABSTRACT

Improving the management of the urban water cycle can reduce greenhouse gas emissions and contribute to climate change mitigation in cities. Stormwater in urban areas has traditionally been collected and conveyed to sewage treatment plants, a practice that has continued with the need to manage increased superficial flow. This paper presents the Low Impact Development (LID) measures to improve water management in the new urban development of Valdebebas in Madrid, and the associated benefits. Stormwater was considered a sub cycle; by shortening the water cycle the local use of rainwater was achieved while reducing energy costs and greenhouse gas emissions for off-site treatment.

The article analyses the urban water cycle from a preventive approach. It considers how urban design features such as topography and pavement selection were used to convey surface water from impermeable areas to permeable ones (vegetated or permeable pavements) and the infiltration of water into engineered soil, reducing the need for off-site conveyance infrastructure, and the amount of water discharged into municipal treatment installations. Moreover, the captured water increases soil water content available for plants and trees which play an important role in absorbing CO_2. Water exceeding soil capacity is collected in the subsurface Sustainable Drainage system (SuDS), including infiltration boxes where water is temporarily stored before moving through the soil toward ground water reserves.

This paper describes the approaches and criteria used to design a large scale SuDS infrastructure in the district of Valdebebas, in northeastern Madrid (Spain), and analyses its performance, followed by a comparison with the predictions under three climate change scenarios, which consider not only the variation in peak flows and runoff, but also the reduction in GHG emissions. Additionally, it presents a sensitivity analysis for the main variables in the design of SuDS, and a multicriteria analysis, to compare the different drainage systems.

1. Introduction

The development of urban areas has increased impervious surfaces, changing the hydrological response of natural catchment areas and drainage patterns. Infiltration has been reduced and runoff has increased, leading to more frequent flooding episodes and water pollution. The effects of climate change on rainfall patterns will make cities even more vulnerable to floods, augmented by spreading urbanization and complex infrastructure systems.

Urban stormwater was formerly considered a waste product, its conveyance and discharge affects receiving waterways causing combined sewer overflows (CSOs), diffuse pollution, etc. (Andrés-Doménech et al., 2010; Balistrocchi et al., 2008). A 10–60% increase in extreme rainfall is predicted in future climate scenarios, with the effects on flood CSOs frequencies and volumes expected to be modified within the same range, depending on the system properties (Willems et al., 2012a). Practical implementation of preventive measures with regard to urban design variables are

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usually considered as consumption-based approaches: entire regions (Su et al., 2016), industrial developments (Dong et al., 2013), specific industrial activities (Wang et al., 2016), residential intensity (Kim and Kim, 2013), urban design (Ho et al., 2013), eco-efficient cities (Wu et al., 2013) or construction alternatives (La Roche, 2010).

In contrast, there is a recent trend considering stormwater management an opportunity to achieve environmental sustainability. During the last decades, holistic approaches for urban water management considering energy efficiency, social amenity uses, biodiversity, urban heat island effect, etc. have been implemented worldwide. However, in Mediterranean cities there has been a limited implementation of these systems (Castro-Fresno et al., 2013; Charlesworth et al., 2013; Perales-Momparler and Valls-Benavides, 2013). Thus, with the Valdebebas project there is an opportunity to demonstrate feasibility and suitability of appropriate methodologies, as a major case study in the Mediterranean area.

1.1. Sustainable drainage systems (SuDS)

LID practices and SuDS, have become an effective tool to restore the natural city hydrology with techniques such as: rainwater harvesting, green roofs and permeable pavements, that have been implemented in urban areas (Andrés-Valeri et al., 2016; Perales-Momparler et al., 2016). The effects and benefits of LID practices on the urban water cycle have been widely addressed (Charlesworth, 2010; Dunnett and Kingsbury, 2004; Guan et al., 2015; Jia et al., 2012; Lundy and Wade, 2011; White, 2002). Elliott and Trowsdale (2007) reviewed 10 LID urban stormwater drainage systems and how they reduced adverse hydrologic and water quality effects in urban developments.

LID measures enhance infiltration in pervious areas by rerouting impervious runoff towards pervious areas, promoting infiltration into the unsaturated zone and increasing the available storage water for local vegetation (Roy et al., 2000; Santos et al., 2009; Shepherd, 2006). Holman-Dodds et al. (2003) observed that the LID measures having impact on natural hydrology were sensitive to soil texture, rainfall intensity and frequency. The major reduction was observed in small, relatively frequent rainfall events and more permeable soils. Even though SuDS have been proven to be very effective and offer multiple benefits, their implementation is still not standardized and major cities still invest in conventional stormwater management approaches.

1.2. Climate change effects

Urban activities have a direct effect on climate change. The predictions for climate change scenarios show different patterns of precipitation, temperature, evapotranspiration, etc. It is expected that these patterns will modify hydrological research and management tools.

The changing pattern of precipitation, temperature and evapotranspiration together with the rapid development of industrial cities during the second half of the twentieth century, have increased greenhouse gas (GHG) emissions, although uncertainty remains in assessing the temporal and spatial variability of these effects (Oreskes, 2004). The estimations of the Intergovernmental Panel on Climate Change (IPCC) for 2100 highlight a rise between 1 °C and 3.5 °C in the global temperature. This will probably increase the precipitation intensity and the number of storm events.

Several studies have dealt with the impact of climate change on stormwater quantity and quality in urban areas. In a case study in central Belgium (Poelmans et al., 2011), results showed that future land cover change in suburban areas will increase peak discharges. The main uncertainty, affecting changes in peak flow and extent of flooding, came from future climate change scenarios. The potential damage associated to floods was mainly influenced by land cover changes. Hamdi et al. (2011) showed the effects of urbanization on surface runoff in an area of Brussels from 1960 to 1999, and predicted how it would respond in different climate change scenarios. Tavakoli et al. (2014) studied the variation of extreme flows in a Flanders region, using the hydrological model WetSpa, considering three scenarios of climate change and urban development. They observed that the extreme peak flows would increase due to climate change and urban growth. Coupling both the effects (climate change and urban development) may lead to increased frequency of river floods (in winter), and extreme low flows (in summer). Putro et al. (2016) identified the impact of climate and land use change on selected water quantity and quality indicators in southern England. In the urban catchments, they observed an increase in runoff and a decrease in the quality indices.

Considering the above context, design criteria in urban areas must be reviewed according to the expected climatic scenarios. Willems et al. (2012b) presented an overview of the methods used to assess the impact of climate change on rainfall extremes at the urban catchment scale. They highlighted that estimation of climate change impact on extreme, local and short-duration rainfall is highly uncertainty and that statistical downscaling and bias correction is required. Also, they recommended comparing and verifying different downscaling assumptions.

1.3. Effects of GHG emissions

Urban activities have a direct effect on climate change as a consequence of GHG emissions, with an energy cost derived from the need to treat waste water in urban areas. Dhakal (2010) determined the global GHG emissions for the urban water cycle, involving the urban context, urban planning and infrastructure design, (transport, water and wastewater management, buildings, and energy supply), technology, consumption and lifestyle.

According to the UN-HABITAT Cities and Climate Change: Global Report on Human Settlements 2011, the world's cities occupy 2% of total land, and are responsible for up to 70% of the GHG emissions. Phillis et al. (2017) assessed city sustainability with the SAFE model (sustainability assessment by fuzzy evaluation), and proposed measures for improvement. European cities ranked at the top on the list of sustainable cities whereas African, Asian, and South American cities ranked at the bottom. Waste generation and GHG emissions were the main problem in cities of the developed world.

GHG emissions for urban planning can be predicted from infrastructure design data. Zubelzu et al. (2015) developed a methodology to characterize them, and proposed preventive measures based on sustainable design criteria. The results indicated that transport is the greatest pollutant, followed by gas and electricity consumption. They also determined the average undeveloped land required for every m^2 of urban land for the complete GHG emissions capture. Likewise, the relationship between carbon emissions allowance and the amount of emissions related to urban and economic development, have also been studied (Jiang et al., 2016; Zeng et al., 2017a,2017b).

Some cities have adopted specific legislation to deal with GHG emissions within the urban water cycle. The City of Madrid has approved an ordinance on the efficient use of water, calling for a reduction in the amount of impermeable paving to where it is strictly necessary (Article 8), and encouraging the collection of rainfall for aquifer recharge (Ayuntamiento de Madrid, 2009), while the Royal Decree 1290/2012 establishes that new urban development projects in Spain should enhance measures to limit stormwater discharge to sewers (article 259ter).

This paper describes the approaches and criteria used to design

a large scale SuDS in the new planned district of Valdebebas (Madrid, Spain). It also analyses its performance which is compared with the predictions under three climate change scenarios, considering not only the variation in peak flows and runoff, but also the reduction in GHG emissions. In addition, it presents a sensitivity analysis for the main variables in the design of SuDS, and a multi-criteria analysis, to study the optimum design point among SuDS.

2. Urban stormwater management in the urban development of Valdebebas

The new planned district of Valdebebas (Fig. 1) in northeastern Madrid (Spain), offers the opportunity to study the results of LID measures taken on a large scale which may provide useful information for future city-wide policies. With a total surface area of 1065 ha, of which half is green open space, the population is expected to reach 45,000–50,000 when fully built out, the population now at around 11,000.

The Valdebebas infrastructure was privately planned and funded by the land owners and handed over to the city of Madrid in exchange for development rights. The first planning stages and negotiations with the Madrid City Council took place between 2001 and 2004. Decisions were made to promote a mixed-use urban development, other Madrid suburban projects of the same period having sectorial land use patterns. Building density was increased to create the critical mass for public transportation with a local train station already in service, several bus lines and two planned subway stations, as well as 27 km of bike paths, with the aim of encouraging the use of mass transport and alternative transport to reduce GHG emissions from vehicular use.

One of the effects of increasing building density was that public green open space was increased to 50% of the site, with an overall benefit in improved environmental conditions for the new district, as compared to the adjacent urban development of Ensanche de Barajas, with only 31% of green open space. The design of green open space, and the public realm in general, was considered of great importance for the success of the project, with parks in place before the first residents arrived to Valdebebas. The increased green open space area has an impact on hydrology, reducing the impervious pavement areas, so reducing the peak flows and the aggregated volumes conveyed to the sewage system.

The parks range from a large forestry area, 380 ha, to a network of interconnected urban linear parks, which provide green open spaces next to homes, but also pedestrian itineraries to enhance walking by residents.

2.1. Low impact development measures

Between 2005 and 2007 the urban infrastructure plans were drawn up and it was decided to embrace LID measures including efficient water management features. Drinking water is a precious commodity in a region with frequent drought conditions, and a growing metropolitan population. The district of Valdebebas was connected to the municipal recycled water system for park irrigation, obtaining recycled water from the local water treatment plant. But recycled water is also limited, and it was necessary to take many other measures to comply with the water assignment for the development and reach the water needs for the planned urban parks and gardens.

The main water efficiency measures adopted were:

- Reduction of water thirsty lawns, accounting for only 3% of the surface area of urban green open spaces. This required replacing traditional lawns with drought tolerant shrub areas and increased plaza areas, shaded by trees. The plant species chosen

Fig. 1. Aerial view of the new planned Valdebebas district in northeastern Madrid (Spain).

were all drought-tolerant, mostly from the Mediterranean region or from other Mediterranean climate areas.

- Installation of subsurface drip irrigation to reduce water loss from evaporation and providing water directly to the root area. The efficiency of this irrigation method being higher than superficial irrigation systems.
- Centrally automated control of the irrigation system, connected to a weather station, which further increases the efficiency of water use and detects irrigation anomalies and water leaks.
- Design and installation of SuDS in all park areas.

2.2. Sustainable urban drainage systems in Valdebebas

At the time of infrastructure specification for Valdebebas, stormwater was traditionally collected and conveyed to the local sewage treatment plants (Fig. 2). At the beginning, the project landscape design team promoted the SuDS, among other things because stormwater could also be a valuable resource and water input for plants.

Thus began the implementation of a system that enhances the overall sustainable objectives for the project, by catchment of stormwater in the landscaped areas, excess water not used by plants percolating to underground infiltration boxes that in turn release and replenish valuable groundwater reserves in order to increase the on-site use of rainwater, while decreasing the energy cost associated to off-site treatment.

The proposal of a SuDS for all of the urban parks and gardens in Valdebebas, initially met with some resistance by city officials since the city was going to receive and maintain the system. However, the overall benefits for the city as compared with a traditional sewage system, including recharging the Valdebebas aquifer, proved to be convincing and a green light was given for what was then considered an experimental urban practice. A total of 18 ha of green areas were designed and built incorporating a sustainable drainage system between 2007 and 2009 (Fig. 3).

The large-scale application of SuDS in stage 1 parks in Valdebebas was precursor to the adoption of the 2009 guidelines in the City of Madrid regarding SuDS.

The pavements in the public parks were both pervious and impervious. The latter to improve the maintenance of areas with heavy foot traffic, but all pavements were sloped toward the planting areas to ensure catchment of stormwater. A scheme of the system can be seen in Fig. 4a.

The project suffered a serious setback derived from the global economic crisis and in 2010 construction was halted. Nearly ten years after installation of the first SuDS in Valdebebas a new set of parks totalling 6 ha were reactivated in 2016 (stage 2) as shown in Fig. 3. These new parks have benefited from the experience acquired from the earlier parks. Pervious capability of the new parks has been improved, with an increased surface area of plantings and permeable paving increased to 65% of the surface area as compared to 53% in stage 1. The SuDS have been enhanced to increase the storage capability for stormwater, while the intention is to monitor water infiltration at certain points in the system. A more sophisticated approach has been used to analyze the movement of rain water, taking into account the local climate conditions, topography, porosity of pavements and soil, etc.

3. Techniques for urban stormwater management

3.1. Criteria for sustainable urban stormwater management

Traditionally, stormwater management consisted in immediate runoff capture and conveyance beyond the urban area, most times without considering the quantity (flows and volumes) and quality effects downstream. In this approach, the Rational Method equation provides the peak flow rates that the system has to transport, where the rainfall intensity and the runoff coefficient are the two parameters to define. The runoff coefficient depends on the impervious surface coverage, and rainfall intensity is defined from the Intensity-Duration-Frequency Curves (IDF Curves) for the site time of concentration.

However, when the stormwater management system introduces detention devices, the duration of the storm is a variable that plays a critical role and also has to be considered. In addition, in complex systems, different design storms (with variation of peak intensity and duration) may be critical for different parts of the systems; hence the use of only one design storm could lead to unsafe results.

In urban systems, with short concentration times, it is important to assess behavior for short and intense storms, but for detention elements, longer storms with lower intensity could be the critical ones to assess due to higher runoff volumes.

The design of stage 1 SuDS in Valdebebas was calculated

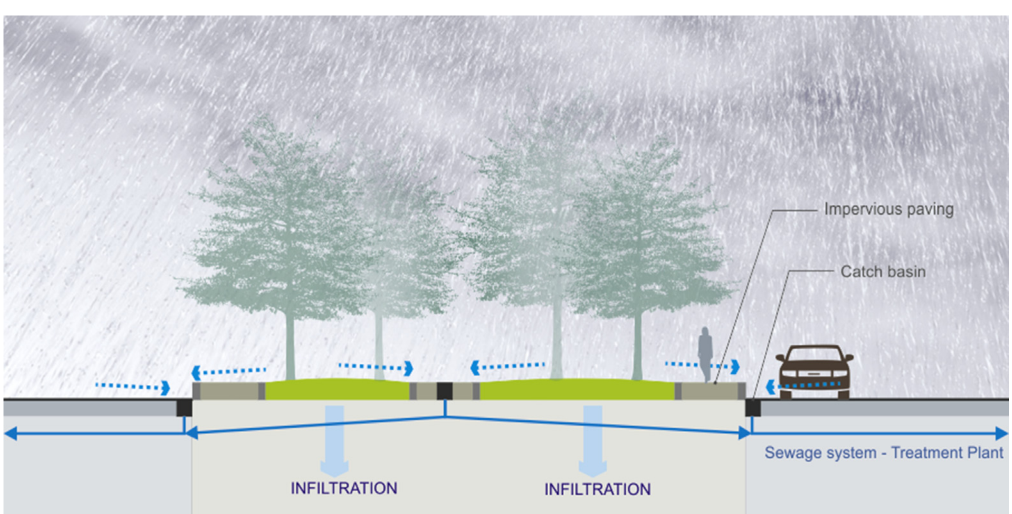

Fig. 2. Sketch for a conventional stormwater management.

Fig. 3. Map of the Valdebebas urban parks with SuDS.

considering a peak flow for a return period of 2 years, deducing the volume capable of storing the area of the storm's hydrograph for a storm with a duration of 100 min.

As stated in the previous section, the experience acquired with the design of stage 1 allowed a fine-tune for the design criteria and further approaches. Thus, this paper will focus on the stage 2, and only occasionally stage 1 will be referred to for comparison purposes. Additionally, the hypothetical use of CuDS in the parks has been analyzed as an exercise to compare the results with the existing SuDS infrastructure.

Six design storms (Table 1) were used for the design of the stormwater management system of stage 2 parks, based on the IDF Curves broadly used by the Madrid City Council (Catalá Moreno, 1989). It is highlighted that the last one is above the return period considered for the city (10 years).

For the SuDS design, not only peak flows but volume management is considered. Hence, a starting point was to define the criteria of the systems being able to fully retain the precipitation volume of 80%, i.e., only 20% of rainy days (daily precipitation) goes above that number. In this study, we consider the historical data series (from 1920 to 2014) for the Madrid Retiro weather station (Spanish National Meteorological Agency, AEMET), with an annual average rainfall of 428 mm, the total daily precipitation for the 80% of rainy days lays below 11 mm. This value is very similar to the total precipitation of event number 2 (see Table 1) hence, the designed systems should completely cope with that storm without overflowing to the conventional network outside the parks.

Furthermore, the stage 2 park system was assessed within a full year, using 10 min intervals events. Year 2007 was considered representative for the whole data series with a total precipitation of 404 mm, and an event of 72 mm/h intensity in 10 min. This was higher that the design intensity for the 10 year return period storm.

The time that the system will take to drain the stored runoff is also a key variable. The SuDS Manual (Woods-Ballard et al., 2015) recommends that it should be half empty in 24 h, and this recommendation has been adopted for the design of the stage 2 parks. Since it is also important to consider the storage of infiltrated water (in addition to other processes such as evapotranspiration), another variable to take into account in the design is the underlying soil permeability. Information from geology maps and the geotechnical research (Euroconsult, 2005) show that these parks will be constructed above aluvio-coluvial deposits (poorly bound materials of heterogeneous permeability) and the Madrid Formation (sands), with an estimated permeability ranging from 10^{-2} to 10^{-3} cm/s. A more detailed site investigation will be undertaken prior to starting the construction works, following the BRE methodology (Building Research Establishment, 1991), in order to verify these values or amend the design as needed. Finally, the SuDs design takes into account a security factor of 10.

Three land uses have been considered regarding the runoff coefficients: impervious pavement ($c = 0.9$), pervious pavement ($c = 0.6$) and planted areas ($c = 0.2$). Table 2 shows the surface areas for every land use and analyzed stage.

The drainage system for stage 2 was calculated using the software MicroDrainage® from XPSolutions (www.xpsolutions.com), providing full hydrograph analysis to test networks for overloading conditions during extreme rainfall events. Fig. 5 shows some images of the infrastructure modelling works.

3.2. GHG emissions calculation

GHG emissions of the urban cycle have been calculated using the software E^{2}STORMED which is an open access decision support tool to include energy and environmental criteria for urban stormwater management decision making. A complete description of the tool can be found in www.estormed.eu and in Morales-Torres et al. (2016).

E^{2}STORMED allows the calculation of the energy consumption

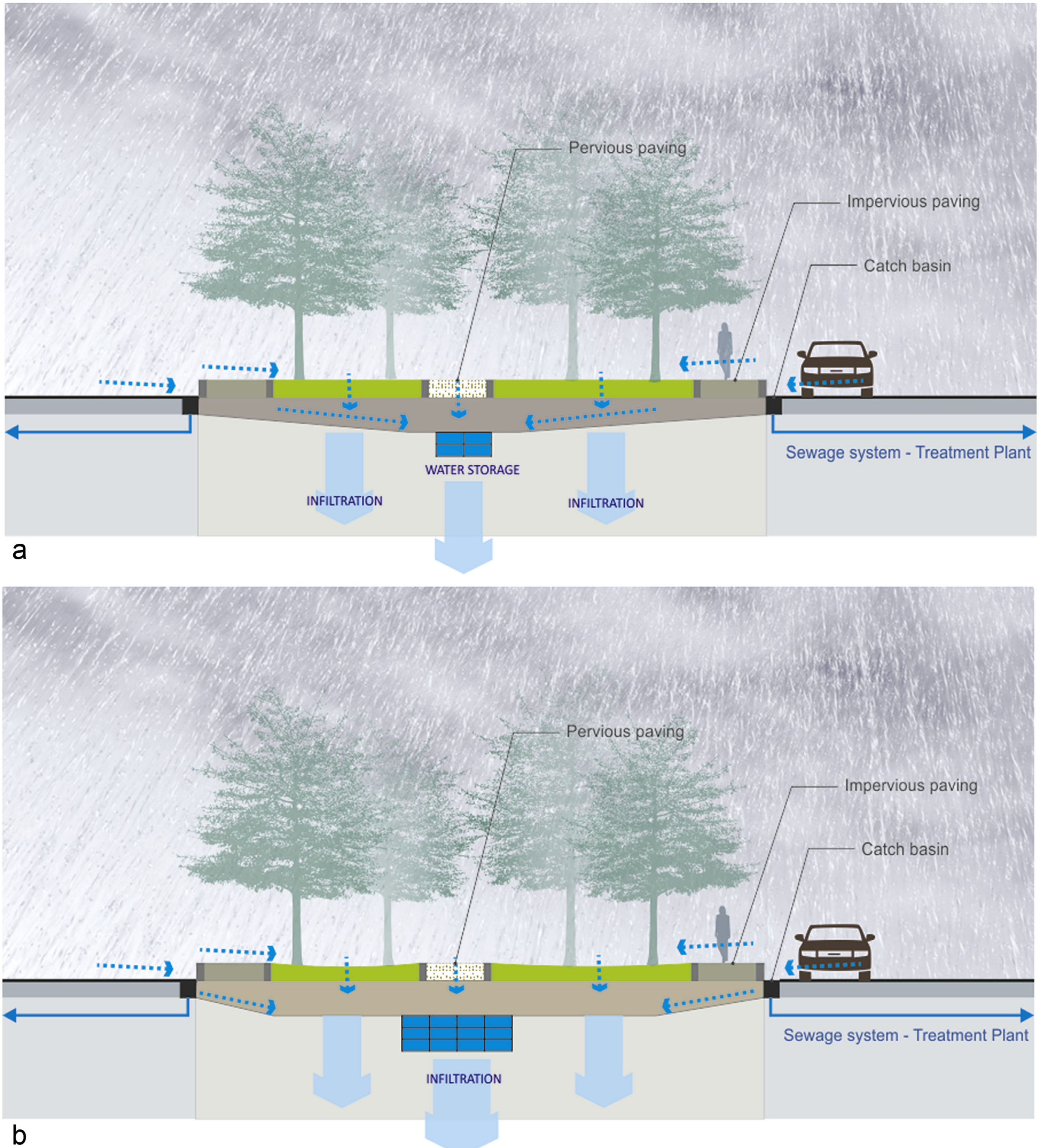

Fig. 4. Scheme of SuDS systems in Valdebebas: (a) installed in 2009, and (b) installed in 2017.

Table 1
Design storms for the design of the stormwater management systems of phase 2 parks in Valdebebas.

Rainfall nº	Return period (years)	Storm time (min)	Intensity (mm/h)	Cumulative precipitation (mm)
1	2	1440	0.7	17.2
2	10	10	67.8	11.3
3	10	15	55.7	13.9
4	10	30	36.5	18.2
5	10	60	21.7	21.7
6	20	10	78.6	13.1

Table 2
Surface areas for each land use in every analyzed stage.

Zone	Impervious pavement (m^2)	Pervious pavement (m^2)	Planted surface (m^2)
Stage 1	86,279.83 (47.08%)	21,563.58 (11.77%)	75,407.46 (41,15%)
Stage 2	20,212.51 (34.95%)	14,356.09 (24.83%)	23,257.07 (40.22%)

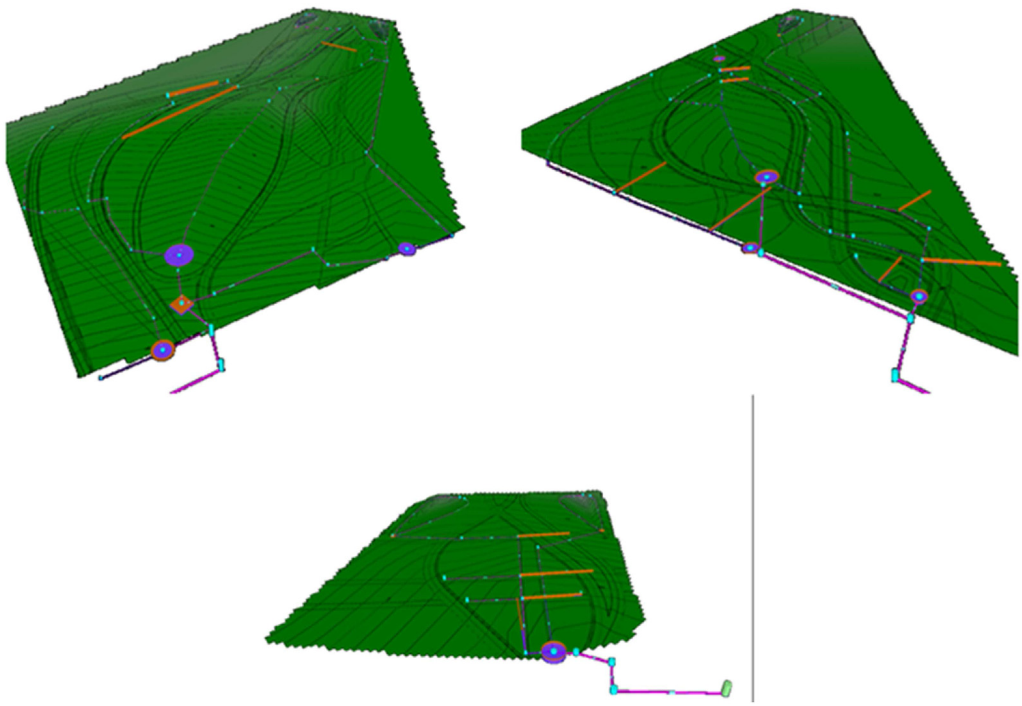

Fig. 5. Drainage infrastructure modelling in Valdebebas phase 2 parks obtained with the MicroDrainage® from XPSolutions.

and the GHG emissions from a life cycle approach (Morales-Torres et al., 2016) considering all the stages from infrastructure construction to the urban water reutilization. The tool includes information to calculate the energy consumption and GHG emissions of drainage infrastructures along their lifespan (not only sustainable drainage systems but also conventional ones). It also incorporates information to define the hydrological cycle in order to calculate its energy consumption and GHG emissions. The software analyzes, among others, the following items: runoff and infiltration volumes; stormwater treatment (including pumping and any other energy consumption, treatment and distribution of drinking water); rainwater harvesting; rainwater reuse; irrigation requirements; flood protection benefits from certain infrastructures and energy building benefits from insulation improvements. In addition, the tool includes modules to incorporate the CO_2 sequestration and ecosystem services which is linked to the analyzed drainage system.

The model yields unitary data (energy consumption, building performance) and emission factors to calculate the energy consumption, and GHG emissions of the aforementioned topics retrieved from international sources. Complementarily, this data can easily be applied to available specific local data.

3.3. Prediction for climate change scenarios

The performance of the SuDS and its differences with CuDS has been analyzed considering climatic change scenarios. First, the actual scenario was studied using rainfall data series (average and maximum) from 1951 to 2014 corresponding to the Barajas-Aeropuerto weather station, near Valdebebas. Second, future climate projections from United Nations Framework Convention on Climate Change (UNFCCC) have been considered. The climatic projections were for the daily maximum rainfall, A1B, A2 and B1 scenarios of the Special Report on Emission Scenarios (SRES) for the Third Assessment Report (Intergovernmental Panel on Climate Change, 2001), and the Representative Concentration Pathways 45 and 85 (RCP45 and RCP85, respectively), of the SRES for the Fifth Assessment Report (Intergovernmental Panel on Climate Change, 2014).

The IDF curves were calculated for the analyzed climatic scenarios (Fig. 6) and the intensity for a 10 min storm was selected following the same criterion than the one adopted for the infrastructure design. It was assumed that the time of concentration in urban basins equals 10 min, and the worst case regarding the discharged flow calculation the duration of the storm equals the time of concentration.

A complete simulation of the behavior of the SuDS installed in each park has been run with the aforementioned climatic projections and criteria.

3.4. Sensitivity analysis for the main design variables

The sensitivity analysis considered two approaches. The first considers the actual situation and the effect of the design variables on the hydrological response. Thus, the cases with and without SuDS have been compared considering current climatological data,

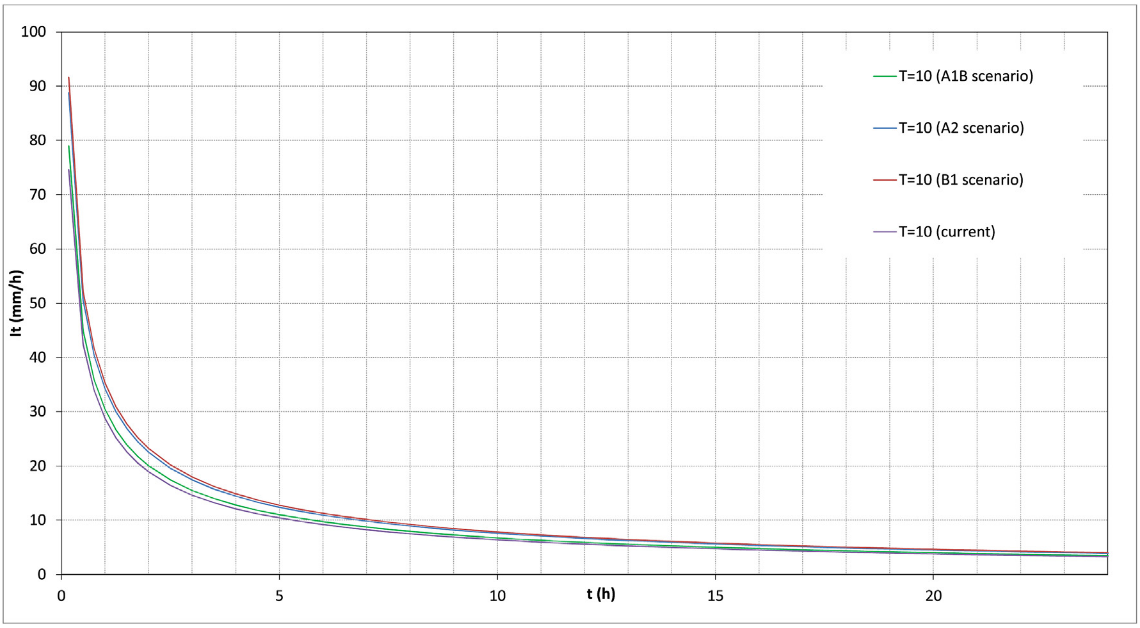

Fig. 6. Intensity-Duration-Frequency curves for different climatic scenarios.

and future climate change forecasts. Likewise, the effect of the runoff coefficient and the permeability of the soil have been analyzed.

The second approach analyzes the hypothetical case without the SuDS infrastructure; the potential system capacity under the assumption that the infrastructure will be able to convey all the generated flows. The potential water volume, which would be conveyed to the municipal sewage system, has been analyzed using the volume of the SuDS storage, and the average runoff coefficient of the park. The last is calculated as the weighted average of every runoff coefficient which considers each type of pavement and planted zones and their occupied area.

Additionally, a multicriteria analysis was performed to study the optimum design among different techniques (CuDS, SuDS stage 1, SuDS stage 2). The criteria selected were: total cost of building and operation (weight = 40%), GHG emissions of wastewater management (weight = 40%), recharge of the aquifer (weight = 15%) and the educational ability (weight = 5%).

4. Analysis of the proposed stormwater management in Valdebebas

The effects of the SuDS on the hydrological response have been assessed for a given storm event, and for a representative year. The storm event provides information about the behavior of the system at a given point in time. It shows the capability of the SuDS to deal with an extreme event, while the representative year relates to the behavior of the general system providing information about aggregated flows and energy balance.

The operation of the designed SuDS was calculated considering the storm on March 27th, 2007. Table 3 depicts the results of the peak flow and volumes sent to the conventional sewer network. As can be observed, the SuDS were more effective than the CuDS showing a significant reduction of the flows and volumes conveyed to the traditional sewer network.

The SuDS also laminate the water storm conveying the runoff to the pervious areas (where it will infiltrate) and reducing the outflow rate (compared to the inflow rate) to the sewage system (Fig. 7).

Both effects, observed for a given storm, reduce the size of the municipal drainage systems needed for extreme events. Likewise, the drainage municipal infrastructures (network pipes, treatment plants, and the hypothetical sewer storage tanks) will be smaller. In addition, the network operation would be smoother, reducing peak flows conveyed to the network.

Table 4 shows the analysis for the representative year 2007 and for the urban parks of stage 2. The volumes discharged to the conventional urban drainage system SuDS were significantly less in SuDS than CuDS. The reduction was higher than 79% in all parks.

As was to be expected, the volumes conveyed to the municipal system are reduced for a whole year and as a consequence the cost (economic, energetic and regarding GHG emissions) decreases. The volume of water not conveyed to the municipal sewage system is stored in the infiltration boxes, and it accounted for 9269.7 m^3. This water will move towards the phreatic level recharging the aquifer, and increasing soil moisture content as well. Although some authors have stated that SuDS could help to increase the soil moisture of the unsaturated zone (Roy et al., 2000; Santos et al., 2009; Shepherd, 2006), further research is needed to assess the ability of these systems to perform as passive irrigation systems. If this fact is confirmed, the SuDS would also reduce water for irrigation as well as water and energy, and GHG emissions (especially with recycled water that requires additional treatments to be used for irrigation).

Fig. 8 shows the SuDS performance under the climate change

Table 3
Peak flow (m^3/s) and volumes (m^3) sent to the conventional sewer network during the pilot event in the stage 2 parks.

Return period	Storm time (min)	Peak flow		Volume	
		CuDS	SuDS	CuDS	SuDS
10	10	0.46	0	338.3	0
2	1440	0.01	0	496.5	0
10	15	0.45	0.05	460.3	24.5
10	30	0.30	0.16	611.9	108
10	60	176.30	129.50	680.8	186.5
20	10	529.20	32.80	388.8	20.2

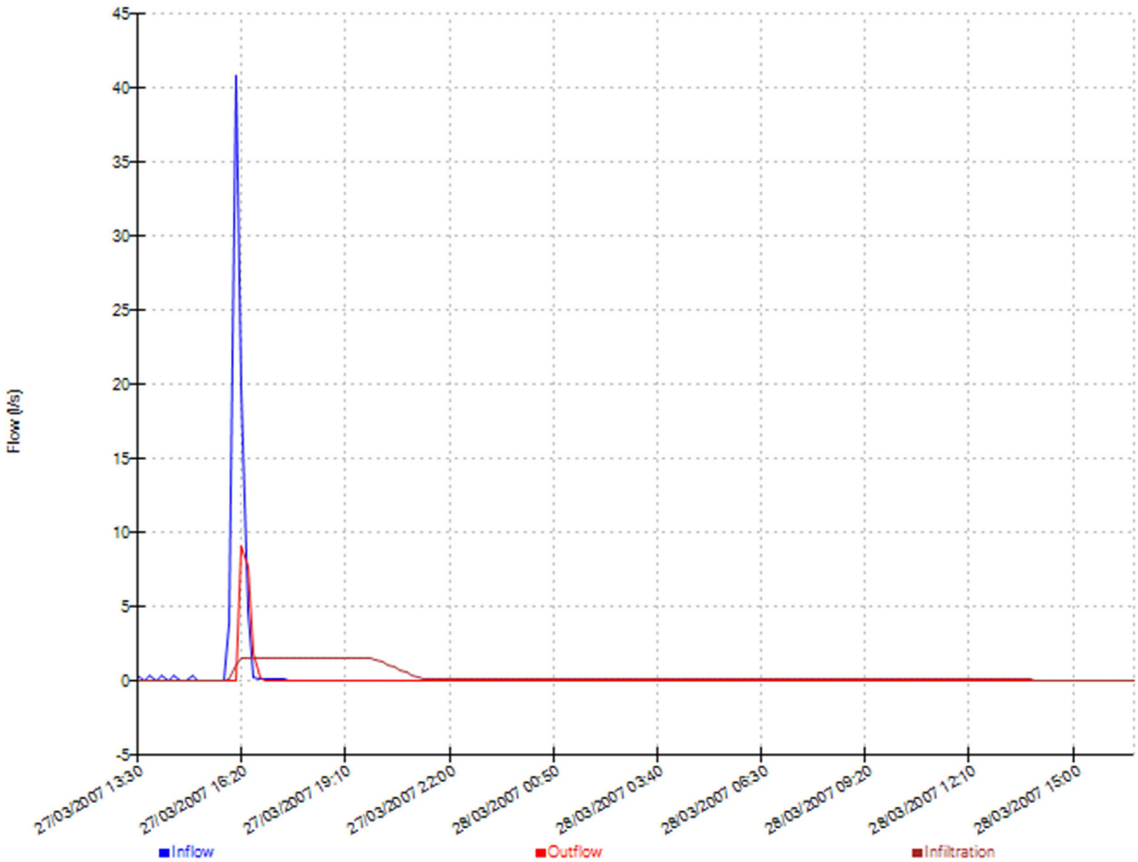

Fig. 7. Inflow, outflow and infiltration hydrographs of stage 2- park 23 for the storm of 03/23/2007.

Table 4
Volumes of stormwater (m^3) conveyed to the conventional sewer system for the stage 2 parks considering the hypothetical case (with CuDS) and the actual situation (with SuDS).

Park	SuDS	CuDS	Reduction (%)
P021	2082.1	237.7	89
P023	1201.1	113.1	91
P033	1107.1	231.7	79
P19a	5439.8	866.7	84
P19b	1013.4	124.6	88
TOTAL	10,843.5	1573.8	85

scenarios. No significant differences are observed between the current situation and the predictions for the three climatic scenarios when considering the climatic monthly average data. The major difference corresponded to the maximum daily values which would affect the hydrographs and hietographs and thus, the design criteria. It is expected that the design peak flow increases as well as the stormwater volume for a given event. Fig. 9 a and b show the hietographs for a 60 min storm and the hydrographs of the park 19 b.

These results agree with the ones from other researchers which highlighted that the peak flows will increase in the climate change scenarios (Putro et al., 2016; Hamdi et al., 2011; Schreider et al., 2000; Tavakoli et al., 2014). The reduction of the peak flows and stormwater volumes in SuDS will be more significant since these systems will smooth the effects of the expected torrential nature of future precipitations. Additionally, as Willems et al. (2012b) stated, the design criteria and techniques must be reviewed according to the expected stormwater scenarios. For example, if the expected peak flow increases, as a result of a greater daily maximum rainfall, the infiltration rate of pavements and soils would decrease. Consequently, the surface runoff would increase, as well as the probability of conveying water to the sewage system. This fact would be is minimized in the design criteria adopted in Valdebebas, where the SuDS have the capacity to laminate the flows, although further research is needed to confirm it. Table 5 illustrates this point, showing the expected peak flows for the three climatic scenarios for every park in stage 2.

SuDS reduce the peak flows discharged to the sewer and, as expected, they will increase in the different climate scenarios, but would be less than those generated if CuDS were installed.

Table 6 shows the energy consumption and the GHG emissions for the analyzed parks and the climatic scenarios. The stormwater management with SuDS reduces about 10% the energy consumption and GHG emissions. The SuDS emissions for the infrastructure construction and operation are greater than in CuDS (additional energy is required to install infiltration boxes) although the difference is small.

Fig. 10 presents the results for the multicriteria analysis for stage 1 and stage 2 parks. All the parks behaved similarly so only the results for park 19b have been displayed.

4.1. Sensitivity analysis

A global measure of sensitivity is given with the first approach of the sensitive analysis which was assessed in both stage parks (stage 1 and stage 2). The stage 1 parks were designed according to criteria commonly used to design drainage networks in the city of Madrid, as it was stated in section 2. Table 7 shows the average water

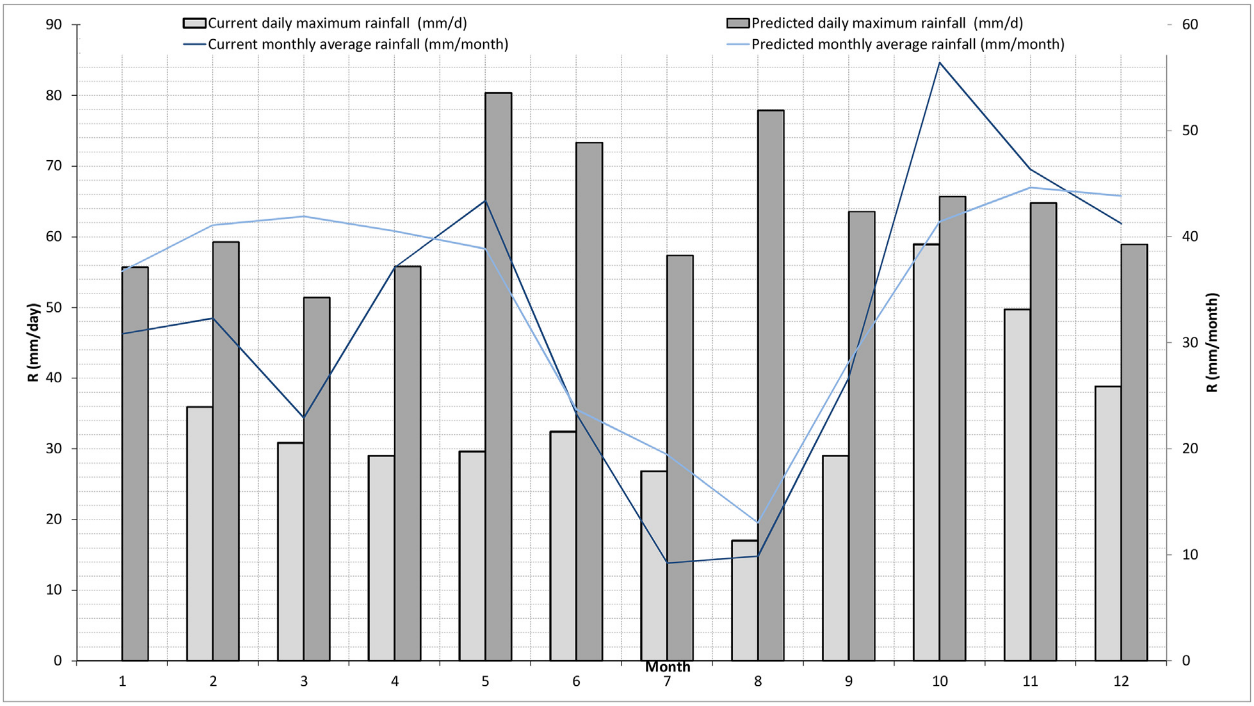

Fig. 8. Comparison between maximum daily and monthly average between current data and future climatic scenarios.

volume conveyed to the conventional urban drainage system considering: the hypothetical situation (with CuDS) and the real situation (with SuDS), and the criteria adopted in the design of stage 1 for all the parks in this stage. The water volume conveyed to the sewage system decreases in SuDS however its reduction is significantly less than the observed in the stage 2 parks (see Table 4)., which highlights that the design criteria adopted for the stage 2 is more efficient.

In addition, Table 8 shows the performance of park 21 under the three climatic scenarios in order to further understand the effect of the climatic change on the operation of the SuDS. For illustrative purposes, the results of the analyzed design storms have also been displayed in Table 8 for the current scenario, both with and without SuDS.

The peak flow and the volumes conveyed to the sewage system increase for all climatic scenarios, however they are less than without SuDS thanks to the retention effect. This would provide resilience to the system and adaptation to the new conditions.

Table 9 shows the values of the peak flow and volumes conveyed to the sewage system for four different design criteria which modify the runoff coefficient C and the soil permeability K. The first corresponds to a case with no SuDS system. The second corresponds to the current impervious pavements ($C = 0.9$ and $K = 0.036$ m/h). The third considers a case where the impervious pavement has been replaced for a more permeable pavement $C = 0.2$ and the same permeability Finally, the four corresponds to a case of a low permeable pavement, $C = 0.9$ and $K = 0.0036$ m/h.

Table 9 shows that the peak flow and volumes conveyed to the sewer system are very sensitive to the reduction of the runoff coefficient. For most of the design storms, their value is almost negligible as C decreased. Conversely, they are less sensitive to the soil permeability variation. For the worst case situation, if soil permeability reduces 10 times, the peak flow and the volume increase 40.9% and 42.9%, respectively. For the representative event, the volume increases over 300% and it would be expected that the peak flow exceeds soil infiltration and consequently, the SuDS would be flooded. Likewise, the excess of water would have to be discharged to the conventional sewage system, although it could be mitigated by increasing the SuDS storage capacity.

Results for the second approach of the sensitivity analysis are shown in Fig. 11 which depicts the variation of the volumes, conveyed both to the municipal sewage system and to the SuDS storage, as the average runoff coefficient C changes. The calculated C variation includes only the effect of the different values for rainfall intensity as Horn and Schwab (1963) stated.

As C increases, the amount of water stored in the SuDS increases. Likewise, the water conveyed to the municipal sewage system decreases up to a limit imposed by the SuDS storage capacity.

Fig. 12 shows the variation of the average volumes conveyed to the sewage system and stored in the SuDS as a result of the variation of their storage capacity V_{DEP}. Although the results might be affected by other variables than the ones studied, they show that there is optimum storage capacity (about 37 m^3), which remains practically constant.

4.2. Applicability and accuracy of the approaches

The present paper presents the approaches and criteria for the design of SuDS, in large scale, introduced in section 3, and analyzes the effect of these systems on: hydrological parameters, energy consumption and GHG emissions under three climatic scenarios. They could be applied for the design of SuDS infrastructure in any urban area, for example, as the one presented in Charlesworth et al. (2013). The studies of Castro-Fresno et al., 2013 and Perales-Momparler et al., 2014, show their performance in other locations with different climatological and hydrological conditions such as Madrid (Spain), Benaguasil (Spain), Aveiro (Portugal), Fiorano (Italy). Also these systems are broadly extended in countries such as Australia, France, the UK and USA.

The technology and criteria for SuDS design do not much differ from conventional urban drainage systems, and specific design criteria can be found in Andrés-Valeri et al. (2016). In addition,

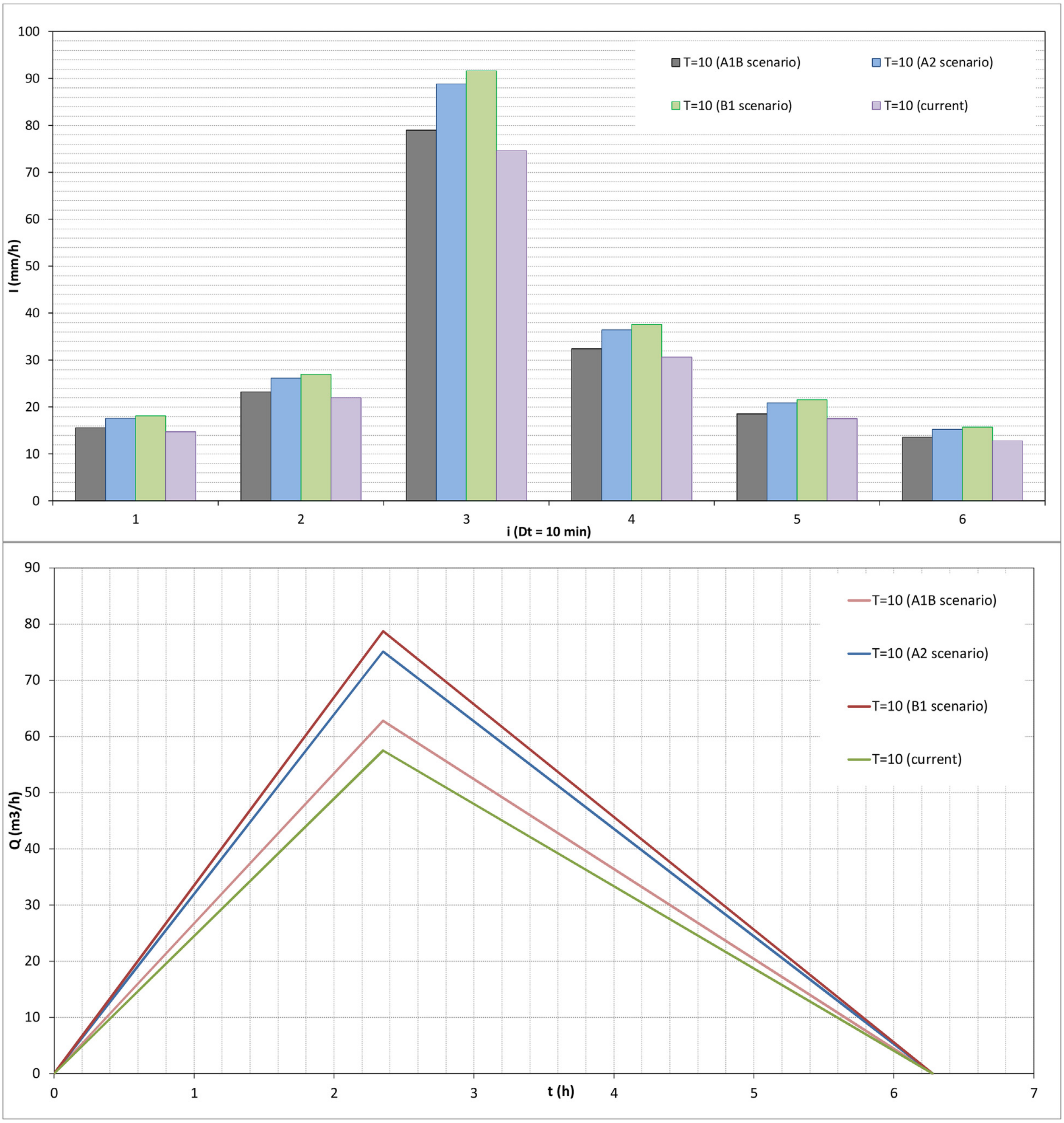

Fig. 9. Current climatic data and different future scenarios for park 19:(a) hietographs and (b) hydrographs.

Table 5
Expected peak flows (l/s) for a 10 min long storm and different climatic scenarios.

Park	Peak flow				
	Current		Predicted (with SuDS)		
	CuDS	Current SuDS	A1B	A2	B1
P021	64.6	2.5	4.9	20	27.4
P023	38.4	0	0	0.5	3.6
P033	33.3	0	1.2	12.3	16.7
P19a	166.7	11.4	21.9	49.3	76.8
P19b	35.3	0	0	0	4.8
TOTAL STAGE 2 parks	338.3	13.9	28	82.1	129.3

SuDS can easily link with the existing traditional urban drainage systems or with the conventional sewage treatment plants.

Any stakeholder can apply the approaches and criteria to develop urban projects. The results from this study, as well as other reported in the cited literature for other places, can be extrapolated to any design conditions. Some specific adjustments could be needed depending on the specific climate or environmental situation, or the design criteria as well. For example, short and intense storm events or soils with poor permeability could require a review of the SuDS design criteria to retain 80% of the precipitation. Nevertheless, as the data exposed in Table 8 showed, the infrastructures are provide flexibility to laminate the events and to retain most of the rainfall before be conveyed to the sewage system which means that the design criteria presented in the present paper should be applicable for different climate conditions.

The results presented in previous works referred in the

Table 6
Energy consumption and GHG emissions for the analyzed parks.

Park	Infrastructure (building; kWh-kgCO_{2eq}/ operation; kWh/y-kgCO_{2eq}/y)		Wastewater management (kWh/y-kgCO_{2eq}/y)	
	Energy consumption	GHG Emissions	Energy consumption	GHG Emissions
CuDS				
P021	1,480,626/1251	451,071/330	945.27	224.86
P023	588,106/526	179,139/139	545.29	129.71
P033	209,608/217	63,808/57	502.62	119.56
P19a	516,342/435	156,921/115	2469.66	587.49
P19b	98,951/126	30,082/34	460.08	109.44
SuDS				
P021	1,467,200/1255	448,080/331	837.35	199.19
P023	589,120/530	180,097/140	493.95	117.50
P033	228,936/221	70,432/59	397.43	94.54
P19a	583,011/439	180,255/116	2076.18	493.89
P19b	100,231/130	30,790/35	403.51	95.99

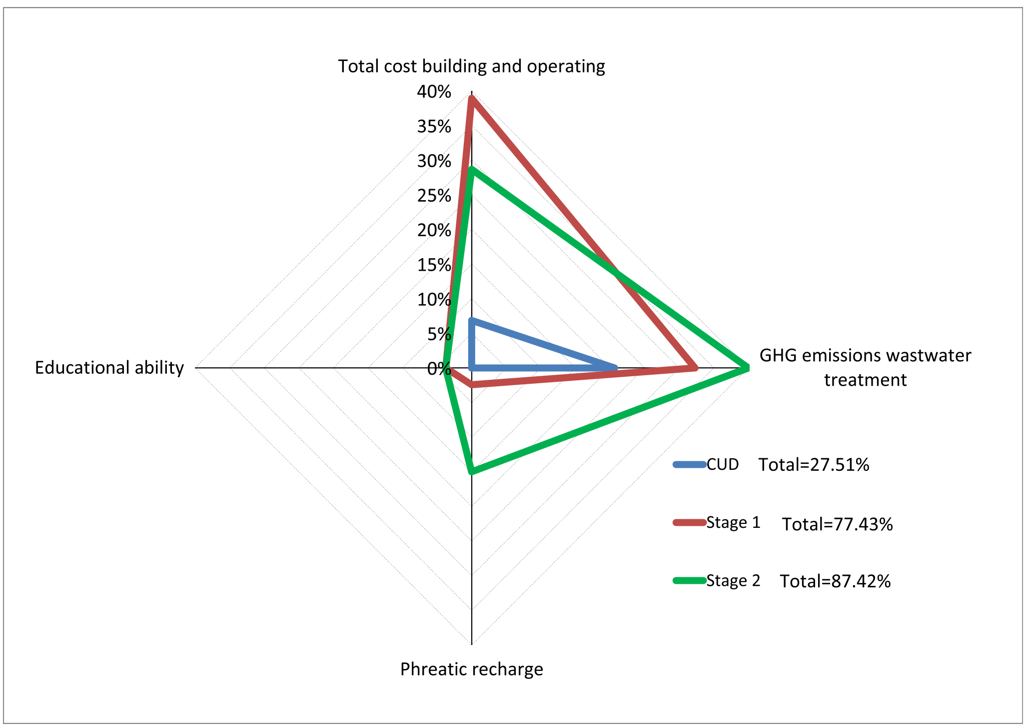

Fig. 10. Multicriteria analysis for park 19b.

Table 7
Daily average volumes (m^3) conveyed to the conventional sewer system for different climatic scenarios in the stage 1 parks considering the hypothetical case (with CuDS) and the actual one (with SuDS).

Scenario	CuDS	SuDS	Reduction (%)
Current	291.12	86.42	44
RCP45	234.31	97.14	41
RCP85	197.29	124.55	44

literature and results of the present work, highlight the advantages of SuDS compared to CuDS. As Table 10 shows, the cost of building the infrastructures does not differ significantly between the two criteria adopted in the present paper (stages 1 and stage 2 parks) but differs considerably between CuDs and SuDs.

Thus with flow reduction, not only the aggregated volume but also the peak flow, conveyed to sewage plants in SuDS. There is a reduction in water surcharge, hence the cost of the municipal infrastructure attributed to the development can likewise decrease. Moreover, with SuDS building costs being inferior, the multicriteria analysis clearly shows that the optimal solution corresponds to a drainage system which includes sustainable infrastructure and adopts the criteria taken in the final stage of park construction in Valdebebas.

Likewise, no relevant deviation between the expected results and the observed behavior have been observed neither in the literature nor throughout Valdebebas, with no unexpected events or surface flooding having been observed from 2009 to present. Thus, the accuracy of the proposed approaches and criteria is adequate. Despite the absence of external deviations, the fact is that there could be deviations between predicted and observed values. For this type of subsurface infrastructure, only monitoring the design variables could shed light on the accuracy of the system. Several types of sensors could be used to obtain data to compare predictions and to prove the accuracy of the model: flowmeters in

Table 8
Peak flow (l/s) and stormwater volumes (m^3) conveyed under the climatic scenarios considering various stormdesign

Design	Scenario	Return period (years)	Storm time (min)	Peak flow (l/s)	Volume (m^3)
Without SuDs	Current	10	10	88.1	64.6
		10	30	57.8	121.1
With SuDS	Current	10	10	0	0
		10	30	22.6	17.7
	A1B	10	10	5.0	3.2
		10	30	38.0	37.5
	A2	10	10	20.3	8
		10	30	50.7	51.7
	B1	10	10	23.9	9.4
		10	30	32.3	29.4

Table 9
Peak flow (l/s) and volumes (m^3) conveyed to the sewage system in park 21, considering different values for the runoff coefficient and soil permeability.

Return period	Storm time	Without SuDS	SuDS K = 0.036 m/h; C = 0.9	SuDS: K = 0.036 m/h; C = 0.2	SuDS: K = 0.0036 m/h; C = 0.9
Peak flow					
10	10	88.1	0	0	0
2	1440	1.1	0	0	0.5
10	15	87.3	12.5	0	14.6
10	30	57.8	22.6	0	25.1
10	60	34.4	17.7	2.3	25.1
20	10	99.8	4.4	0	6.2
Representative event 3/27/2007		73.7	18	6.4	36.9
Year 2007		73.7	18	0	21.9
Volume					
10	10	64.6	0	0	0
2	1440	98.8	0	0	10.1
10	15	82	5.2	0	6.9
10	30	121.1	17.7	0	25.3
10	60	133.8	29.6	1.3	42.3
20	10	74.7	3	0	4.5
Representative event 3/27/2007		2082.1	237.7	49.5	773.3
Year 2007		94.4	19.5	0	27.6

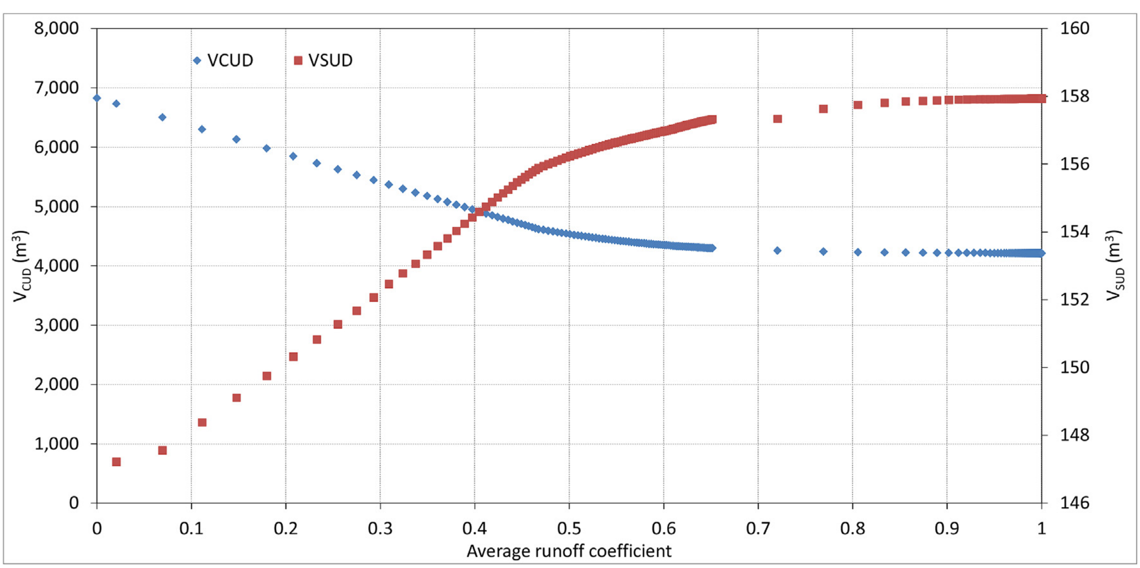

Fig. 11. SuDs systems: Annual aggregated volume stored (VSUD) and conveyed to the municipal sewage system (VCUD) versus the average runoff coefficient.

the pipes to monitor the discharged flows, level probes in the storage systems to monitor the stored water, soil moisture sensors to record the infiltration of water from the storage units, infiltration tests, etc.

5. Conclusions and recommendations

This study shows that the SuDS approach and criteria adopted for stormwater management in Valdebebas has proved to be a sustainable use of water. The analysis of SuDS in stage 1 and stage 2

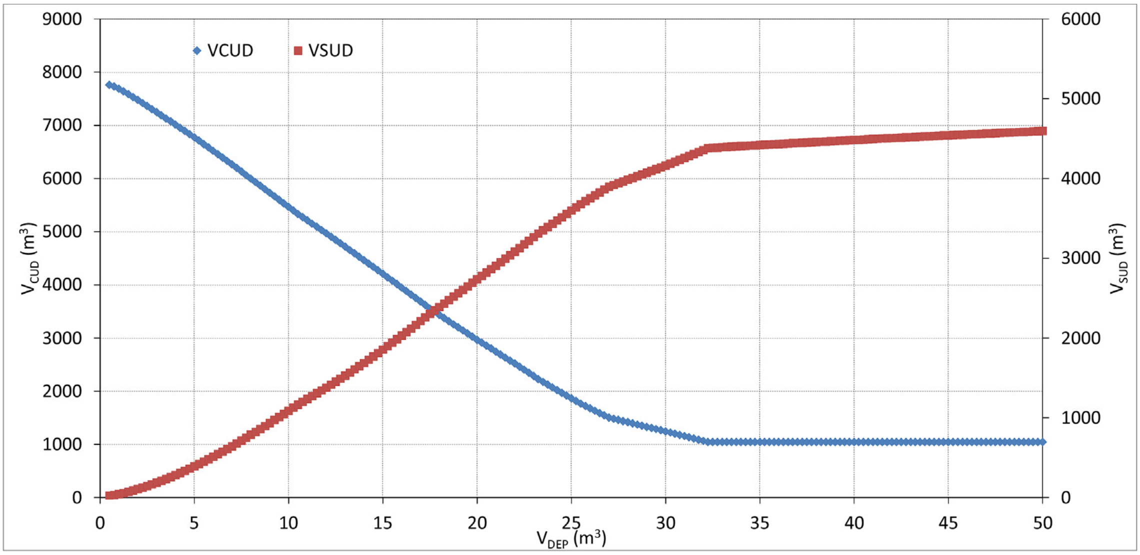

Fig. 12. SuDs systems: Annual aggregated volume stored (VSUD) and conveyed to the municipal sewage system (VCUD) versus the SUD storage capacity.

Table 10
Unitary cost (€/m^2) of building the drainage infrastructure in CuDS and SuDS (stage 1 and stage 2 parks).

CuDS	SuDS Stage 1	SuDS Stage 2
6.03	1.06	1.39

parks has shown a reduction of over 41% in the average water volume conveyed to the conventional urban drainage system, as compared to CuDS, the reduction being higher in stage 2 parks.

In the analyzed parks and climatic scenarios, the use of SuDS has reduced energy consumption and the GHG emissions by about 10%, thus contributing to the global efforts to combat climate change.

Furthermore, building costs of SuDS infrastructure in Valdebebas, as compared to CuDS, has shown to be inferior.

For all the above, the SuDS adopted for stormwater management in Valdebebas parks are clearly an asset to the project, and the city as a whole, while offering additional diverse environmental services such as facilitating the local reuse of water to maintain soil moisture, of benefit to urban landscaping, while enabling the aquifer to be recharged. With a future increase in use of SuDS, city water treatment infrastructure will be able to downscale as treatment needs are reduced.

Consequently, any stakeholder should consider using SuDS systems in urban development projects, given the many advantages from an environmental point of view and significant cost reductions, including reduced water treatment surcharges. The results from this work, as well as others reported in the cited literature, can be adapted to different situations and local conditions.

The rainfall duration has shown to clearly affect the design of SuDS, hence it will be necessary to consider several rainfall events for an appropriate stormdesign. The effects of climate change must clearly be considered in designing SuDS, to add resilience to the system

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